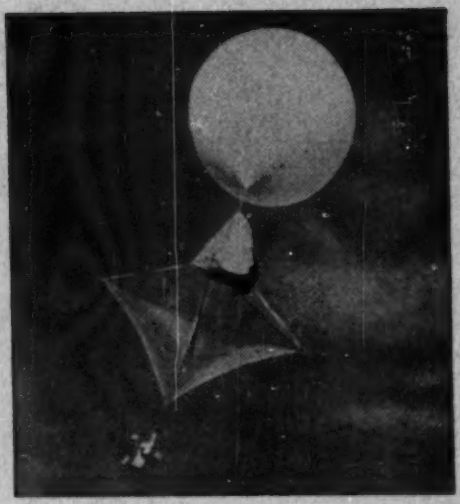
M.O.751
METEOROLOGICAL OFFICE

the meteorological magazine

JANUARY 1964 No 1098 Vol 93
Her Majesty's Stationery Office



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AIRFLOW AROUND A MODEL OF THE ROCK OF GIBRALTAR

Scientific Paper No. 18

By J. Briggs, B.A.

For certain adverse winds, those from south-east through south to south-west, severe turbulence in the lee of the Rock of Gibraltar can affect the runway at North Front, and also the approaches to the runway. This paper gives an account of wind tunnel work designed to map out the areas of strong turbulence near the runway for these adverse winds.

Diagrams are presented which indicate the likely areas of rough and smooth air, at heights between 500 and 3,500 feet and for winds between south-east and south-west, near the runway. The diagrams are based on observations of the fluctuations of smoke in the airflow around a scale model of the Rock.

A theoretical discussion of the relation of model airflow to real airflow suggests that the diagrams can give useful indication of the turbulent areas in the lee of the actual Rock.

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METEOROLOGICAL OFFICE M.O.751

THE METEOROLOGICAL MAGAZINE

Vol. 93, No. 1098, January 1964

LONG-RANGE FORECASTS BY THE METEOROLOGICAL OFFICE

By the DIRECTOR-GENERAL

On 13 November 1963 the Secretary of State for Air announced, in a written answer to a Parliamentary Question, that a decision had been taken to publish monthly weather prospects prepared by the Meteorological Office.

The publication consists of a single sheet. The front is devoted to the climatology of Britain for the forecast month in the form of a short descriptive passage followed by tables and maps of climatological averages for 31 stations throughout the country. The back of the sheet has (*a*) an account of the actual weather in Britain during the month just past, (*b*) northern hemisphere maps of (i) mean pressure at sea level and (ii) temperature anomalies of the lower half of the atmosphere (1000–500 mb) for most of the month just past, (*c*) a general survey of the large-scale weather patterns of the month just past and inference therefrom, (*d*) weather prospects for the coming month and (*e*) a note on interpretation and use of the prospects.

On the 15th of the month a statement on weather prospects for the next 30 days will be published, so that every month there will be two forecasts, overlapping for a fortnight.

The decision follows research on minor climatic fluctuations and long-term trends that began, about eight years ago, with the statistical investigations of Mr. J. M. Craddock and his co-workers. During this period Mr. H. H. Lamb also studied climatic variations over much longer periods. Gradually, these investigations led to the formation of a systematic approach to the forecasting problem, and since 1960 there have been available written monthly forecasts which could be analysed for evidence of skill, i.e. of a degree of success above that which would result from chance. The analysis indicated that these forecasts do show skill and therefore could be of value to many interests.

The method currently in use depends principally on finding months in earlier years with such a degree of resemblance to the month just past that their sequels may be expected to give some guidance about the coming month.

This resemblance is sought in:

(i) The synoptic sequence over the British Isles. Using a high-speed computer, numerical comparisons of the sequence of the past month are made with the same months in a type calendar going back to 1873.

(ii) The temperature anomaly pattern over a large part of the northern hemisphere. Numerical comparisons are made using various indices of similarity, again with the aid of a computer.

(iii) The monthly mean pressure chart over much of the northern hemisphere. This is at present being done visually.

This procedure usually results in ten or twelve possible analogous months and the daily synoptic maps for these months are then examined. Any months in which, say, the tracks of depressions across the Atlantic, the strength and position of the Azores anticyclone or the pressure distribution in high latitudes differ appreciably from the past month are rejected as unsuitable analogues. The sequels of the remainder (usually two, three or four) are then examined and in the absence of uniformity additional arguments are used to establish what weighting should be given to the various indications. These arguments may be based on the limits of the polar ice pack, sea temperatures, snow cover or some marked anomaly of the general circulation.

The forecasts will usually say:

(i) whether the mean temperature of the month is expected to be average, above, much above, below or much below average;

(ii) whether the total rainfall is expected to be above, near or below average; and

(iii) something about the expected sequence, or the predominant character of the month, e.g. more than the usual amount of northerly weather types.

It will be noted that this system differs in many respects from those used elsewhere, e.g. by the United States Weather Bureau, which depends chiefly on extrapolations from trends in the large-scale atmospheric circulation as shown by the patterns of the hemispherical 700 mb surface. No reliance is placed on statistical relations, either with terrestrial anomalies or with extra-terrestrial events, such as an abundance or deficiency of sunspots. The Meteorological Office method is to argue by physical reasoning, using past situations as a guide.

It should hardly be necessary to emphasize, in a professional journal, that there will be no attempt to predict the day-by-day variations of weather in the coming month. The 'prospects' will do no more than state in broad terms, the expectation of mean temperature and rainfall for the period in relation to long-term or climatic averages, together with some indication of the sequence of weather types for the next 30 days. Nor will any attempt be made to foresee the character of a coming season.

Long-range forecasting is recognized by meteorologists as the most formidable problem in the science of the atmosphere. Attempts to find a solution go back for many years with a depressing chronicle of high hopes not realized. One has only to recall the immense but abortive efforts that have been made to discover significant periodicities, or correlations between extra-terrestrial phenomena (such as sunspots) and weather. The economic value of a reliable system of long-range forecasting is beyond question and it is for this reason, and for the intrinsic interest of the problem, that in the Office research has been intensified in recent years. At present, and probably for some time to come, the preparation of the forecasts will remain the responsibility of the Synoptic

Climatology Branch (M.O.13), with the newly formed Dynamic Climatology Branch (M.O.20) conducting basic mathematical investigations into the general circulation and large-scale features of the atmosphere. The decision to institute a regular service, which was made after the results of the trials had been examined by both the Meteorological Research Committee and the Meteorological Committee, does not imply a major break-through in the problem. Instead, it reflects the fact that the methods now in use are capable of producing forecasts that on a majority of occasions can be useful guides, but it is freely acknowledged that in the present state of the art, a single forecast might be so wide of the mark as to be misleading. This is a risk that must be accepted, as it is in short-range weather forecasting. The monthly weather prospects will be of the greatest value if they are used in conjunction with the daily forecasts and it is hoped that this will become the accepted practice.

EXPANSION OF METEOROLOGICAL OFFICE RESEARCH IN DYNAMICAL CLIMATOLOGY

By R. C. SUTCLIFFE—Director of Research

It is commonly accepted that among the advances in meteorology during the last twenty years a leading place must be given to the development of the basic dynamical theory of depressions and anticyclones and of large-scale synoptic systems generally. Like many another success story it has been the result of the exploitation of a lucky break, we might say a lucky break-through, it having been discovered that in this particular part of the spectrum of meteorological disturbances the behaviour can be largely explained by ignoring all other processes, all other parts of the spectrum. Without considering the origin of the energy, in the non-adiabatic differential heating and cooling of the atmosphere, or the dissipation of the energy, ultimately through smaller-scale disturbances, developments on the large synoptic scale have been explained sufficiently completely to provide a firm basis for forecasting by fundamental calculation: numerical weather prediction in the accepted phrase.

The soft spot in the spectrum having been discovered, further progress could be almost guaranteed by assigning able people to the task of exploitation and in the Meteorological Office the branch for Dynamical Research, headed by Mr. E. Knighting, has made important and well known contributions. In the course of the work, improved understanding and greater success has come in part by invading the wings of the spectrum, taking account of 'friction' on the one hand and 'non-adiabatic processes' on the other, but it is not to be expected that the many distinct problems of dynamical meteorology will yield to attack developed from this one salient and, with encouragement given by success, aided by the mechanized weapon of electronic computing, theoreticians are looking for new points of entry: the Meteorological Office aims to adapt its organization to provide facilities. Within the existing branch of Dynamical Research, M.O.11, attention is being given to the dynamics of fronts, and arrangements have been made to use an Atlas computer, the most advanced high-speed computer yet available, as may be necessary in the course of the research. This may be looked upon as an extension into the smaller scale of meteorological events. At the same time it is hoped to make progress on the larger-scale problems, the general circulation of the atmosphere and the variations on the time-scale of weeks and longer which must be understood if

long-range forecasting is to be put on a sound scientific basis or the theories of climatic change or climatic control are to be raised above the level of speculation.

Progress will depend, as always, first upon the skill and insight of the people concerned but good organization has a modest part to play and in the Office the successful policy of establishing teams of about six research scientists headed by a Senior Principal Scientific Officer and supported by ancillary staff has once more been followed by dividing the old branch for Climatological Research into two, the one to carry the name Synoptic Climatological Research, the other Dynamical Climatological Research. There is nothing in a name—except that it is a handle—but in these cases the names are reasonably indicative of the objectives in mind. Synoptic climatology implies the analysis of the structure of climate with interest directed to geographical distributions and to practical prediction for different parts of the world. In this branch, taking the old number M.O.13, with Mr. M. H. Freeman as its first head and Assistant Director, practical long-range forecasting will be an important interest. Dynamical climatology (accepting the distinction drawn in the American *Glossary of Meteorology**)gives emphasis rather to the fundamental theoretical approach and to the behaviour of the atmosphere as a whole, the general circulation in other words, and this defines closely enough the task of the new branch M.O.20 which Mr. G. A. Corby will lead. That the two branches will have many points of contact goes without saying.

The problems are very difficult and it is far from clear how progress is to be accomplished, but the importance of the subject fully justifies this further investment in research. It may be an investment for capital growth over the next ten years with little in the way of short-term dividend. We must wait and see.

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SOIL TEMPERATURES DURING THE FROST OF EARLY 1963 IN SOUTH-EAST ENGLAND, PART—I

By E. N. LAWRENCE, B.Sc.

Summary.—Minimum soil temperatures and the rates of change of soil temperature at various depths during the very cold winter of early 1963 are given in tabulated form for three types of soil—sand, loam and clay. Further tables give a sequence of temperature changes in these soils at various depths at the end of January 1963, and tables are given also for long period absolute minimum values of soil temperature.

After a short account of soil physics with special reference to soil freezing and thawing, the following topics are discussed for various stations in south-east England: depth of freezing; effects of snow cover, and of soil type and condition on soil temperature.

Introduction.—It is estimated[1] that the three months of December 1962 and January and February 1963 were the coldest in the English lowlands since 1740, judged by the mean air temperature over the period, and that the Thames in the central London area might well have frozen over, had it not been for artificial warming. Soil temperatures during the recent winter are therefore of special interest. Change of soil temperature normally lags behind that of air temperature and thus the period of extremely low soil temperature was delayed until January 1963. A common yardstick by which to judge winter severity is depth of frozen soil, but this factor varies according to topography, as early 1963 reports confirm. In the present paper, air and soil data

*HUSCHLE, R. E.; Glossary of Meteorology. Boston, Mass., American Meteorological Society. Boston, Mass., 1959, p. 184.

from Kew Observatory (mainly sandy loam over rubble) are compared* with those from Woburn, Bedfordshire (sandy soil), Rothamsted, Hertfordshire (clay with flints) and Cardington, Bedfordshire (clay with flints).

At Kew Observatory, data are available from the old, long established site (A) and also from a new, more open site (B). The position of the old site (A) is shown in the *Observatories' Year Book*[2] for 1960, and the new site (B) is about 80 yards to the south-south-east. The old site is on freely drained disturbed soil with sandy loam (0–15 in.) quickly merging into rubble (composed of mortar, broken brick and tiles) with a layer of sandy clay-loam from 3 ft 6 in. down to at least 4 ft. The new site which has an impeded profile drainage is on alluvial soil, with sandy loam (0–6 in.) changing gradually to become clay loam and silty clay by 3 ft down to at least 4 ft.

The soil thermometers used are described in the *Handbook of meteorological instruments*.[3] Soil data for Kew (site A), Woburn, Rothamsted and Cardington are as indicated in Tables I, II and III. The programme at Kew (site B) from 14 February 1963 includes observations of soil surface temperature using a grass minimum thermometer placed on the bare ground. Surface temperatures over grass have been found to correspond to ground surface radiative temperatures.[4,5] When snow is lying the surface thermometer would normally be covered. It should be noted that the term 'bare soil' may include snow-covered soil as opposed to snow-covered grass.

Throughout this account soil at a temperature below 0°C will be referred to as frozen soil, notwithstanding that there may be a small depression of the freezing-point on account of dissolved materials in soil moisture. Values of maximum concentrations of soluble salts in soil, estimated from data given by Baver[6] and Harper,[7] suggest an effect on the freezing-point much below measurable limits. Furthermore, from atmospheric chemistry observations (see for example, tables in *Tellus*, 1959),[8] it is clear that the monthly mean total soluble salt concentration in rainwater, inland in England, never exceeds $N/100$ (and rarely $N/1000$), where N is the gram equivalent weight of salt per litre. Therefore any depression of the freezing-point of soil is neglected in the present calculations.

Soil physics and soil freezing mechanism.—The soil surface layer is heated or cooled by radiation and atmospheric advection, and heat is transmitted through the soil by conduction. Cooling by evaporation may be considerable but is usually very limited in midwinter in the British Isles; warming by condensation and deposition is normally small; the transfer of heat by sublimation may be important and is discussed later with the effects of snow cover. When the ground surface is warmer than the surrounding air, the effect of wind or turbulence is to remove heat from the surface layer and thereby to reduce any heat supply available for conduction downwards: that is, the stronger the wind, the less effective is the radiative heating of the soil surface during daylight—this is particularly noticeable during periods of sunshine.[9] Conversely, by night, air motion may inhibit surface cooling and consequently also the upward flux of soil heat. Thus wind speed as well as air temperature greatly influences the soil temperature régime.

*The air temperatures for Kew are those measured in the standard thermometer screen and not the 'North Wall' screen.

Temperatures at Woburn and Rothamsted were recorded in °F and so some main conversions to °C are shown in the Tables and text to allow direct comparison with Kew and Cardington data which are reported in °C. Similarly, snow depths in in. have been shown also in cm.

Soil temperature changes in a homogeneous soil may be described approximately by the well known equation:

$$\frac{\partial\theta}{\partial t} = a\frac{\partial^2\theta}{\partial z^2}$$

where θ is soil temperature at time t and depth z, and a is the coefficient of thermal diffusivity as defined by the formula

a = thermal conductivity/(specific heat × density)

where all terms refer to soil, and the thermal conductivity is assumed to be constant.

The general behaviour of soil temperature variation with depth may be explained by assuming that the thermal diffusivity is constant. However it has been shown[10] that diffusivity is not generally constant with depth, most especially in the top 10 cm where a tenfold variation may occur. The significant variation of diffusivity in the top soil layer is exhibited for example by data from a grass-covered clay site near Cambridge[11] and also by data given by Johnson and Davies[12] for natural grass-covered chalky soil in the area of Porton (Wiltshire).

The main cause of differences in thermal diffusivity can be attributed to varying water content. Moderately wet soil has much better thermal conductivity than dry soil. This leads to a greater thermal diffusivity because at lower water contents, soil density and specific heat increase much less rapidly with increase of moisture content.

The soil acts as a reservoir of heat and so, with the onset of autumn, there is an increase in mean temperature with depth and any freezing tends to penetrate gradually downwards. However, during marginal freezing weather, intermittent thawing may possibly occur at and near the surface, with a thawing at the bottom of the frozen layer. While the heavier, water-holding clay soils tend to be slow to change in temperature, on account of the high specific heat and latent heat of water (or ice), the better drained sandy soils may experience comparatively rapid changes in water content, and the transfer of heat by water percolation may be considerable. The degree of percolation is dependent not only on the soil type but also on drainage facilities: examples of sudden changes in soil temperatures and further discussion may be found elsewhere.[13,14,15]

From a study of Kew (site A) data, Wright[16] suggested that between depths of 10 cm and 20 cm, grass interfered with the normal course of heat conduction but that the annual variation of temperature between depths of 20 cm and 122 cm is in accordance with the simple theory of heat conduction. He compared data from the grass-covered sandy loam at Kew with data from bare sand at Potsdam, and found that at Potsdam (where one would expect the diffusivity to be higher) the average range of temperature at a depth of 10 cm was about twice that at Kew, and at a depth of 20 cm about three times. Wright found also that, at both these depths, maximum temperatures were reached about 1½ hours earlier at Potsdam and that diurnal variation extended to greater depths there.

Soil thawing process.—As with the freezing process, heavier soils tend to thaw more slowly. For example, at a depth of 4 ft, there is a tendency for later and even lower absolute minima than in better drained soils. Towards the end of winter, thaws are more liable to be rapid, with warming penetrating

quickly downwards from the surface. Rapid major thaws during midwinter in south-east England are normally associated with the advection of warmer air: indeed it is estimated that solar radiation without advectional energy would be insufficient to effect such a change. However, when the surface warms slowly (e.g. in midwinter with limited advection and especially with thick snow cover), any downward heat flux is small and tends to be masked by the reversal of temperature gradient at lower levels and the tendency for an upward flux of terrestrial heat: under such conditions, there is no systematic downward penetration of thawing. As with freezing, thawing may be inhibited by snow cover (but see later).

General weather near the ground during the winter 1962–63.—Synoptic and general climatological details are published elsewhere, for example in the *Monthly Weather Report** (which includes monthly charts of 'Anomaly of mean 1 foot earth temperature in the U.K.'), the *Daily Weather Report*,* *Daily Aerological Record*,* and corresponding summaries, and in an assessment by Booth[17] of the winter of 1963 until mid-February. However it is useful here to summarize a few relevant details.

Snow was covering the ground at 0900 GMT on each day at Kew from 27 December 1962 to 27 January 1963, inclusive, and in February from the 1st–7th and on the 11th and 12th; there was no snow cover in March. At Cardington snow cover was rather more persistent, whereas at Rothamsted and Woburn generally deeper snow persisted continuously from 27 December 1962 until 2 March 1963, inclusive. In late December 1962, before the snow covered the ground, air temperatures at Kew were considerably below average and winds were mainly easterly with some strong or gale force gusts. January 1963 continued very cold with day maximum temperatures at Kew below freezing-point on the 1st, 11th–13th, 17th–24th, and with strong easterly or north-easterly winds from the 17th–21st. After a temporary warming towards the end of January (see Table III(*b*)—columns for air temperatures) the cold spell returned on the 30th and lasted until 6 February. Thereafter, until 23 February, air temperatures remained between −2.5°C and +4.6°C but from 24 February to 3 March, a further cold spell occurred with grass minima varying from −6 to −11°C. On 4 March, the onset of south-westerly winds marked the end of the cold spells of early 1963.

Similar changes of air temperature occurred at Woburn, Rothamsted and Cardington but at Cardington there were markedly lower minimum temperatures presumably caused by topographical effects.

Soil freezing spells during the winter of 1962–63.—During December 1962 there was only a temporary freezing at Kew to a depth of 4 in., and although late December and January were very cold with strong day-time winds, deep soil freezing was delayed till about mid-January because of the usual lag in change of soil temperature behind that of air temperature.

Soil freezing during early 1963 at Kew occurred mainly in two spells:

(i) from about mid-January to about mid-February (though the peak in the fourth week of January was followed by a temporary and shallow thaw at the end of January), and

*Meteorological Office. Monthly Weather Report. London, HMSO.
Meteorological Office. Daily Weather Report. London, HMSO.
Meteorological Office. Daily Aerological Record. London, HMSO.

(ii) a shorter and less severe spell during the last few days of February and the first few days of March.

Allowing for the natural lag, this sequence corresponds with that of the general weather. The Kew (site A) temperatures under grass showed a gradual penetration of freezing from 4 in. to 8 in. to 1 ft in January; however the thaw of mid-February was so gradual that downward progression was masked. Following the thaw in early March, temperatures at depths of 4 in., 8in. and 1 ft rose rapidly, thus illustrating a seasonal singularity of soil climate.[14]

Depth of freezing.—According to a personal communication from H. H. Lamb, studies of old records indicate that the last winter with comparable soil temperature extremes was in the year 1684, but that winter was a little colder and also rather more prolonged and continued into March. In that year, which is believed to have been fairly snow free, it is estimated that in east Somerset (in the region of, but not actually on, the Mendip Hills) frost penetrated to a depth of 1.5 to 2 ft into dry ground and 3 to 4 ft into wet ground. It is reported that similar conditions occurred at two snow-cleared sites near London during the recent winter and that these conditions were confirmed by reports of freezing pipes at 3 to 4 ft below cleared ground.

The data are insufficient to define the extreme depth of freezing soil under natural snow cover during 1963, but a rough estimate may be obtained by extrapolation. It was found that during the anticyclonic conditions prevailing on 23 and 24 January 1963—at the climax of the 1963 cold spells—the 0900 GMT soil temperatures under grass at Kew (site A) were very similar to absolute minimum soil temperatures (see Table I(*b*)), and decreased linearly with depth from 4 in. to 1 ft. This 'linear' effect was previously found for 0900 temperatures following anticyclonic nights at Rothamsted, and has been demonstrated theoretically,[9] albeit in the absence of snow cover. In both situations, temperatures were therefore such as to satisfy the equation derived for general heat conductivity in soil under 'steady state' conditions:

$$a \frac{\partial^2 \theta}{\partial z^2} = 0 \ .$$

By linear extrapolation (and incidentally also by graphical interpolation with the 4 ft temperature), it is suggested that frost extended below the natural snow cover to a depth of about 1.5 ft under grass at Kew (site A) in early 1963, and probably to a depth of 1.5 to 2 ft under bare soil at this site.

During early 1963, freezing of heavy clay soils in south-east England probably did not extend beyond a depth of 1 ft: there was no evidence of freezing at a depth of 1 ft at the clay site at Rothamsted (Table I(*c*)) or even at the exposed though lower clay site of Cardington (Table I(*d*)) where the maximum depth of snow cover reported was 15 cm. However, at well drained sandy sites, the depth of freezing may well have exceeded that at Kew; the extreme temperatures at Woburn (sand) suggest a maximum depth of freezing similar to that at Kew, though the 'linear' effect at Woburn is not so marked, probably on account of the greater variation of thermal diffusivity with depth. The effect of soil type is further discussed in a later section.

Effect of snow cover.—Snow cover generally tends to inhibit change of soil temperature. Because of the snow's albedo, the absorption of solar radiation is restricted and surface temperatures tend to be low so that a steep temperature gradient is liable to be established in the snow layer. Under suitable

conditions this appears to be sufficient for appreciable changes in temperature below the snow cover. It is noteworthy that during the period of thick snow cover, 20–23 January 1963, the soil temperatures at Kew at depths of 4 in., 8 in. and 1 ft (under grass and under bare soil) continued to decrease generally, and that therefore penetration of frost probably continued under the snow. Details of soil and air temperatures and snow cover for Kew and other stations are given in Table III.

In a study of heat transfer in snow, Yen[18] concluded that vapour processes make a significant contribution to the process of heat transfer associated with a natural snow cover. Experimental work[19] on artificially compressed snow subjected to a temperature gradient of about 10°C (−1°C to −12°C) through a sample depth of about 50 cm, for a period of 5 days, showed that 0.135 gm/cm³ of snow was transferred by sublimation from the portion of the sample at higher temperature to the portion at lower temperature. Yosida[20] calculated the heat transfer by diffusion of water vapour and found it to be $2.2 \times 10^{-4} \times$ (temperature gradient) cal/cm³sec for snow at 0°C. Table III(*b*) gives some indication of the order of magnitude of the temperature gradient in snow at Kew: for example, on 23 January the 0900 GMT air (screen) minimum temperature was −12.1°C, the overnight grass[21] minimum temperature was −15.8°C, and with snow depth of 13 cm the 0900 GMT soil temperature was −2.6°C at a depth of 4 in. under grass. (The Table gives the soil temperature only for the 28th and the 24-hour changes during the previous week.)

It is interesting to note that, after freezing, soil temperatures at a depth of 4 in. under grass at Kew exceeded 0°C (at 1800 and 2100 GMT on 27 January 1963) when general snow cover (greater than half cover and depth 4 cm) was still being reported: at these times the soil was still frozen at 8 in. and 1 ft under grass and at 4 in. and 8 in. under bare soil. The occurrence of thawed top soil, at the end of the thaw of a thick snow layer, is not surprising in view of the increases of soil temperature associated with thawing snow (Table III and later sections refer).

Effect of soil type and condition.—The effect of soil type is shown clearly by a comparison of absolute minimum soil temperatures (see Tables I and II). In January 1963, the minimum at a depth of 4 in. under the bare loam at Kew (site A) is just midway between that for Woburn (sand) and that for Rothamsted (clay). This is comparable with what one would expect for the relation between grass minima on these types of soil. At a depth of 8 in. under bare soil and at 1 ft below grass, the minima for Kew and Woburn are very similar (Woburn being only slightly lower) and both are substantially below those for Rothamsted where no freezing was observed at a depth of 1 ft. At a depth of 4 ft, the January minima were very similar for all three sites, but it is interesting to note that for the quarter January–March 1963, the lowest temperature was recorded at Rothamsted, in March. Although snow cover had disappeared by the time of this minimum, the water-holding clay would be slower to warm up, and at a depth of 4 ft was still giving heat to colder layers above.

Equally marked were the differences in the rates of decrease of temperature (under snow cover) which preceded these absolute minima (see Tables I and III). For example, the maximum 24-hour (0900–0900 GMT) decreases of temperature at 4 in. and 8 in. under bare soil and 1 ft under grass (see Table

III(*a*), (*b*) and (*c*)) were greatest at Woburn (except at 8 in.) and least at Rothamsted. At Kew (site A), the corresponding changes were intermediate but at a depth of 8 in., the changes at Kew and Woburn were rather similar. The relation between these rates of decrease, at least at a depth of 4 in., may be considered typical of the soil types and to reflect their relative diffusivities. At lower depths, soil differences are masked by the normal damping of range of temperature with depth and by the general increase of water content.

The effect of soil type during the temporary warming of late January was similarly demonstrated (see Table III). The largest sustained increase of soil temperature at a depth of 4 in. under bare soil (due partly to percolation[13,14] of melted snow) occurred at the sandy site of Woburn while increases at the clay site of Rothamsted were the least conspicuous, the clay soil being impervious (at least at this time of the year when cracking would be absent) and also the warmest soil initially. Increases of soil temperature at a depth of 4 in. under the bare loam soil at Kew (site A) were generally intermediate between these extremes (though the largest single 24-hour (0900–0900 GMT) increase at a depth of 4 in. occurred at Kew). Even before the air temperature increase of 26 January, there were appreciable increases of soil temperature, especially at Woburn (see Table III(*a*)) where the higher diffusivity of the wet sand would be particularly favourable to the upward flux of terrestrial heat from below. The largest post-minimum increase (at a depth of 4 in.) occurred at Woburn in spite of the deeper snow layer there; deeper or more persistent snow cover is not unusual in sandier areas. At depths of 8 in. and 1 ft at Rothamsted, the rates of increase of soil temperature were small and distinctly less than at Kew and Woburn.

At Rothamsted under poor drainage conditions the maximum 24-hour (0900–0900 GMT) increase of soil temperature at a depth of 8 in. under bare soil in January 1963 occurred early in the month in non-freezing soil under 11 in. of snow. This maximum was presumably caused by the insulating effect of snow cover with a consequent restriction of radiation and convection losses, and by the upward flux of heat from below. There was a slight decrease in temperature at depths of 1, 2 and 4 ft.

The effect of soil type or condition on soil temperature is particularly complex during snow cover which itself partly depends on soil type and condition, and on ground cover. A most interesting example of the difference in persistence of snow cover over rough grass, rolled grass and bare soil was observed at Harpenden[22] during a previous winter. It appears that when the soil temperature at a depth of 4 in. exceeded the screen air temperature and melting depended more on the upward flux of soil heat, snow melted first where it was in better thermal contact with the ground, that is over rolled grass or bare soil: but when the air temperature exceeded the soil temperature at a depth of 4 in. (downward flux of heat), snow melted first from the rough grass where contact with and exchange of free air was greater. (The explanation for the latter, which is given in the original paper[22] does not appear to be acceptable.)

Rapid changes of soil temperature can occur only in well drained soils.[13,14] When a sandy soil becomes waterlogged because of bad drainage, or when it retains water because of a high humus content, such a soil will behave more like a heavy soil. In early 1963, the similar soil temperature minima at Woburn and Kew at 8 in. under bare soil and 1 ft under grass (Table I(*a*) and (*b*)) may well have been caused by a decrease with depth of drainage facilities at

Woburn or alternatively by the freely drained rubble subsoil at Kew (site A). The equalizing influence of high water content is well demonstrated by the relations found by Sarson[23] between rainfall and soil temperatures for clay and sandy soils. The monthly July rainfall at Woburn (R) has a correlation of −0.69 with the July monthly soil temperature excess (y), of Woburn (sand) over Rothamsted (clay), for a depth of 1 ft under grass, for the period 1930–50. More generally R and y are related by the formula,[23]

$$y = 2.4 - 0.5954\,(R - 2.31) - 0.0378\,(T - 64.5)$$

with a multiple correlation coefficient of −0.68, where T is the July monthly mean temperature in °F at a depth of 1 ft under grass at Woburn, and 2.31 and 64.5 are the July averages of rainfall in inches and soil temperature in °F respectively, for the period 1930–50 at Woburn.

Acknowledgements.—The author is indebted to the Director, Lawes Agricultural Trust, Rothamsted Experimental Station and Mr. C. A. Thorold, B.Sc., Lawes Agricultural Trust, Woburn Experimental Station for the supply of special data used in this investigation, and to Mr. B. Wilkinson, M.Sc., Regional Soil Chemist, South-east Region, National Agricultural Advisory Service, Ministry of Agriculture, Fisheries and Food for the soil morphological data and much useful discussion, particularly on soluble salt content of soils.

Note.—Part II, to be published in February, will include the following topics: variation of soil temperatures over short distances; diurnal variation; differences between grass-covered and bare soil; and past climatological extremes of soil temperature.

TABLE II—LONG-PERIOD ABSOLUTE MINIMUM SOIL TEMPERATURES UNDER GRASS, AT 0900 GMT ‡

Station	Symons thermometer at 1 foot				Symons thermometer at 4 feet			
	Temperature		Date(s)	Snow depth at 0900 GMT	Temperature		Date(s)	Snow depth at 0900 GMT
	°F	°C			°F	°C		
Woburn (sand)	29.0	−1.7	21 Jan. 1940	<6in. (15 cm)	39.4	4.1	17–19 March 1947 inclusive	Nil†
Kew (Site A) (loam etc.)	31.3	−0.4	21 Jan. 1940 24 Jan. 1940	Partial cover** ≤1 cm**	37.9	3.3	12 March 1947	Nil§§
Rothamsted (clay)	32.0§	0.0	18–23 Feb. 1929 3 March 1929 21 Jan. 1940 22 Jan. 1940 25 Jan. 1940	Nil Nil 0.75in. (2 cm) drifts drifts	36.3	2.4	19–22 March 1947 inclusive	Nil††

Station	Period
Woburn	June 1918–Dec. 1962 inclusive*
Kew (Site A)	July 1903–Dec. 1962 inclusive
Rothamsted	May 1926–Dec. 1962 inclusive at 1 foot. Oct. 1945–Dec. 1962 inclusive at 4 feet.

*Data for depth of 4 feet are not available from Oct. 1924–May 1926 inclusive, and for Jan. 1931. ** At 0700 GMT. †Up to 9 in. earlier in March and snow cover (≤ 6 in.) throughout Feb. 1947. ††Up to 9 in. earlier in March and snow cover (up to 3–4 in.) throughout Feb. 1947, with drifts to greater depths. §At 1 foot under bare soil, absolute minimum temperature for period 1915–62 inclusive was 30.8°F (−0.7°C) on 21 Jan. 1940. §§Up to 10 cm earlier in March and snow cover (up to 13 cm but generally ≤ 2 cm) throughout Feb. 1947. ‡At 1000 GMT before 1915.

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TABLE I—ABSOLUTE MINIMUM SOIL TEMPERATURES AND RATES OF CHANGE OF SOIL TEMPERATURE IN EARLY 1963

(a) WOBURN EXPERIMENTAL STATION, (sand), 52°01′N, 0°35′W: 291 feet above M.S.L. JANUARY 1963

Type of soil cover	Bare soil			Grass	
Type of thermometer	Bent-stem*			Symons**	
Depth of thermometer	4 inches	8 inches	1 foot	2 feet	4 feet
†Absolute minimum °F	22.4	27.8	29.4	33.8	39.7
°C	−5.3	−2.3	−1.4	+1.0	+4.3
Date of absolute minimum	24th	24th	24th	28th, 29th, 30th	31st
Snow depth at 0900 GMT on the same day in inches (cm)	7(18)	7(18)	7(18)	4(10) on 28th 3(8) on 29th 3(8) on 30th	3(8)
Maximum 24-hour decrease (°F)	4.4	2.1	1.7	0.7	0.3
Initial temperature (°F), and date/time (GMT) of beginning of maximum 24-hour decrease.	29.4, 21/0900	30.0, 22/2100	31.1, 23/0900	34.7, 25/0900	various on several occasions
Maximum 6-hour decrease (°F)	⩾ 1.5	1.0	**	**	**
Initial temperature (°F), and date/time (GMT) of beginning of maximum 6-hour decrease.	⩽ 28.0 (between 21/2100 with 28.0°F and 22/0900 with 25.0°F)	28.9, 23/1500	**	**	**
Maximum 24-hour increase (°F)	4.8	1.8	0.8	0.2	Fairly
Initial temperature (°F), and date/time GMT of beginning of maximum 24-hour increase.	24.1, 25/2100	28.2, 25/2100	29.8, 26/0900	33.8, 30/0900	steady decrease
Maximum 6-hour increase (°F)	2.8	0.8	**	**	**
Initial temperature (°F), and date/time (GMT) of beginning of maximum 6-hour increase.	22.4, 24/0900	29.2, 26/1500	**	**	**

*Observations at 0900, 1500 and 2100 GMT only. **Observations at 0900 GMT only.
†These values are also the absolute minima for the period January–March, inclusive, 1963 except as follows:
(i) At 2 ft, 33.7°F (0.9°C) on 5 March 1963, no snow. (ii) At 4 ft, 37.7°F (3.2°C) on 11 and 12 March 1963, no snow.

TABLE I—ABSOLUTE MINIMUM SOIL TEMPERATURES AND RATES OF CHANGE OF SOIL TEMPERATURE IN EARLY 1963—*continued*

(b) KEW OBSERVATORY (SITE A), (loam etc.), 51°28′N, 0°19′W: 18 feet above M.S.L. JANUARY 1963

Type of soil cover	Bare soil			Grass			
Type of thermometer	Bent-stem*		Bent-stem*		Symons**		
Depth of thermometer	4 inches	8 inches	4 inches	8 inches	1 foot	1 foot	4 feet
†Absolute minimum °C	−2.8	−2.2	−2.7	−2.1	−1.2	−1.3	+3.7
°F	27.0	28.0	27.1	28.2	29.8	29.7	38.7
Date/time (GMT) of absolute minimum	23/0900	23/1500 23/1800 26/0600	23/1200 24/0600	26/0600	26/0600 26/0900	24/0900 26/0900	30/0900 31/0900
Snow depth at 0900 GMT on same day in cm.	13	13 on 23rd 12 on 26th	13 on 23rd 13 on 24th	12	12	13 on 24th 12 on 26th	Nil
Maximum 24-hour decrease (°C) Initial temperature (°C), and date/time (GMT) of beginning of maximum 24-hour decrease.	1.6 −0.7, 18/1800	1.0 −1.2, 22/1500 22/1800	1.1 −0.2, 17/0900	0.6 various on several occasions	0.5 −0.3, 22/1200	0.5 −0.6, 22/0900	0.2 various on several occasions
††Maximum 3-hour decrease (°C) Initial temperature (°C), and date/time (GMT) of beginning of maximum 3-hour decrease.	1.4 −0.9, 19/1500	0.5 −0.6, 19/1500	0.6 −1.1, 19/1500	0.2 various on several occasions	0.3 +1.1, 11/0600	•• ••	•• ••
Maximum 24-hour increase (°C) Initial temperature (°C), and date/time (GMT) of beginning of maximum 24-hour increase.	2.0 −2.4, 25/1800 −2.3, 25/2100	1.6 −2.2, 26/0600	2.1 −2.6, 26/0600	1.5 −2.1, 26/0600	0.8 −1.2, 26/0900 −1.1, 26/1500	0.9 −1.3, 26/0900	Fairly steady decrease
§Maximum 3-hour increase (°C) Initial temperature (°C), and date/time (GMT) of beginning of maximum 3-hour increase.	0.7 −0.6, 14/1200 −2.8, 23/0900	0.5 −2.2, 23/1800 −1.8, 26/1200 −1.3, 26/1500	0.4 −2.7, 23/1200 −1.9, 26/1200 −1.5, 26/1500	0.5 +0.6, 1/0600	0.2 various on several occasions	•• ••	•• ••

*Observations at 0600, 0900, 1200, 1500, 1800 and 2100 GMT. **Observations at 0900 GMT only.
†These values are also the absolute minima for the period January–March, inclusive, in 1963 except as follows: at 4 ft, 3.2°C (37.8°F) on 4,5,6 and 8 March.
††Maximum decreases in °C between 2100 and 0600 GMT are as follows: (i) At 4 in. and 8 in. under bare soil, 0.7 and 0.6 respectively.
(ii) At 4 in., 8 in. and 1 ft under grass, 1.0, 0.5 and 0.2 respectively.
§Maximum increases in °C between 2100 and 0600 GMT are as follows: (i) At 4 in. and 8 in. under bare soil, 0.2 and 0.4 respectively.
(ii) At 4 in., 8 in. and 1 ft under grass, 0.6, 0.3, and 0.2 respectively.

TABLE I—ABSOLUTE MINIMUM SOIL TEMPERATURES AND RATES OF CHANGE OF SOIL TEMPERATURE IN EARLY 1963—*continued*

(*c*) ROTHAMSTED EXPERIMENTAL STATION, (clay), 51°48′N, 0°22′W; 420 feet above M.S.L.

(i) JANUARY 1963

Type of soil cover	Bare soil			Grass				
Type of thermometer	Bent-stem		Symons	Bent-stem			Symons	
Depth of thermometer	4 inches	8 inches	1 foot	4 inches	8 inches	1 foot	2 feet	4 feet
*Absolute minimum °F	31.2	32.8	32.9	30.6	31.8	33.2	36.0	39.0
°C	−0.4	+0.4	+0.5	−0.8	−0.1	+0.7	+2.2	+3.9
Date of absolute minimum	25th	26th and 27th	24th and 28th	25th	27th	26th	26th	31st
*Snow depth on same day, in inches (cm)	5(13)	4(10) on 26th 2(5) on 27th	5(13) on 24th 2(5) on 28th	5(13)	2(5)	4(10)	4(10)	2(5)
Maximum 24-hour decrease (°F)	0.7	0.2	0.5	1.2	0.7	0.5	0.3	0.3
Initial temperature (°F), and date of beginning of maximum 24-hour decrease.	32.5 on 23rd	33.6 on 12th 33.4 on 13th 33.2 on 22nd	33.5 on 22nd	32.2 on 22nd	33.0 on 23rd	34.0 on 23rd	36.5 on 23rd	40.7 on 16th
Maximum 24-hour increase (°F)	0.8	0.5	0.4	1.0	0.6	0.1	0.2	0.1
Initial temperature (°F), and date of beginning of maximum 24-hour increase.	31.2 on 25th	33.4 on 4th	33.5 on 12th	31.1 on 26th	31.8 on 27th	various on several occasions	36.6 on 17th	40.4 on 17th

(ii) JANUARY–MARCH 1963

*Absolute minimum °F	28.9	32.0	32.1	30.2	31.8	32.9	34.9	37.1
°C	−1.7	0.0	+0.1	−1.0	−0.1	+0.5	+1.6	+2.8
Date of absolute minimum	1 March	1,3,4 March	4 March	1 March	27 Jan.	2–6 March inclusive	4,5,6 March	10,11 March
*Snow depth on same day in inches (cm)	1(3)	1(3) on 1 March nil on 3,4 March	Nil	1(3)	2(5)	1(3) on 2 March nil on 3–6 March	Nil	Nil

*Observations at 0900 GMT only.

TABLE I—ABSOLUTE MINIMUM SOIL TEMPERATURES AND RATES OF CHANGE OF SOIL TEMPERATURE IN EARLY 1963—*continued*

(*d*) CARDINGTON, (clay), 52°06′N, 0°25′W: 93 feet above M.S.L. JANUARY 1963

Type of soil cover	Grass			Grass	
Type of thermometer		Bent-stem*		Symons**	
Depth of thermometer	2 inches	4 inches	8 inches	1 foot	4 feet
†Absolute minimum °C	−2.9	−2.6	−0.8	+0.1	+3.4
°F	26.8	27.3	30.6	32.2	38.1
Date/time (GMT) of absolute minimum	24/0600 24/0900	24/0900	several occasions	25/0900, 26/0900 27/0900, 28/0900	30/0900 31/0900
Snow depth at 0900 GMT on the same day in cm.	15	15	various	15 on 25th, 13 on 26th 5 on 27th, 1 on 28th	Nil on 30th 1 on 31st
Maximum 24-hour decrease (°C)	1.2	1.0	0.6	0.3	Steady decrease
Initial temperature (°C), and date/time (GMT) of beginning of maximum 24-hour decrease.	−0.9, 10/0900	−0.4, 11/0300 −0.6, 11/0600	−0.2, 18/1200	+1.5, 9/0900	
Maximum 3-hour decrease (°C)	0.7	0.5	0.7††	**	**
Initial temperature (°C), and date/time (GMT) of beginning of maximum 3-hour decrease.	−1.4, 11/2100	−2.1, 24/0600	−0.1, 19/0900	**	**
Maximum 24-hour increase (°C)	1.9	1.3	0.6††	0.1	Fairly steady decrease
Initial temperature (°C), and date/time (GMT) of beginning of maximum 24-hour increase.	−2.3, 25/2400	−1.9, 25/2400	−0.8, 19/1200	various on several occasions	
Maximum 3-hour increase (°C)	0.7	0.4	0.3	**	**
Initial temperature (°C), and date/time (GMT) of beginning of maximum 3-hour increase.	−1.8, 12/1500 −2.2, 18/1200	−1.5, 12/1500 −2.6, 24/0900 −1.6, 26/0900	−0.6, 19/1500	**	**

*Observations at 0300, 0600, 0900, 1200, 1500, 1800, 2100, and 2400 GMT. **Observations at 0900 GMT only.

†These values are also the absolute minima for the period January–March, inclusive, 1963 except as follows: at 4 ft, 2.4°C (36.3°F) on 8 March, no snow.

††Value of soil temperature at 1200 on 19 January suspect; next largest 3-hour decrease 0.2°C, and next largest 24-hour increase 0.5°C.

TABLE III—CHANGES IN SOIL TEMPERATURE AT VARIOUS DEPTHS IN LATE JANUARY 1963, WITH ASSOCIATED AIR TEMPERATURES AND SNOW DEPTHS

(a) WOBURN EXPERIMENTAL STATION

Type of soil cover	24-hour change in soil temperature					Air screen temperature				**Grass thermometer temperature: overnight minimum		Snow depth at 0900 GMT at end of period	
Type of thermometer	Bare soil Bent-stem		Grass Symons			Minimum		Maximum					
Depth of thermometer	4 inches	8 inches	1 foot	2 feet	4 feet	°F	°C	°F	°C	°F	°C	*inches*	*centimetres*
24-hour period ending 0900 GMT on	*degrees Fahrenheit*			*degrees Fahrenheit*									
21st	−0.2	0.0	−0.1*	−0.2*	−0.1*	23	−5.0	29	−1.7	27	−2.8	8	20
22nd	−4.4	−0.9	−0.4	0.0*	−0.1*	−2	−18.9	28	−2.2	9	−12.8	8	20
23rd	−2.1	−1.0	−0.6	0.0*	−0.1*	−4	−20.0	23	−5.0	8	−13.3	8	20
24th	−0.5	−1.3	−1.7	−0.3*	−0.3*	−1	−18.3	25	−3.9	7	−13.9	7	18
25th	+1.6	+0.8	+0.3	0.0*	−0.1*	6	−14.4	21	−6.1	12	−11.1	7	18
26th	+3.0	+0.4	+0.1	−0.7*	−0.1*	11	−11.7	34	+1.1	13	−10.6	7	18
27th	+2.7	+1.2	+0.8	0.0*	−0.1*	32	0.0	36	+3.3	21	−6.1	6	15
28th	+1.4	+0.9	+0.5	−0.2*	−0.1*	33	+0.6	37	+2.8	31	−0.6	4	10
Temperature at 0900 GMT on 28th in °F	31.1	31.1	31.1	33.8	39.9								
°C	−0.5	−0.5	−0.5	1.0	4.4								

(b) KEW OBSERVATORY (SITE A)

Type of soil cover	24-hour change in soil temperature							Air screen temperature		**Grass thermometer temperature: overnight minimum	Snow depth at 0900 GMT at end of period
Type of thermometer	Bare soil Bent-stem		Grass Bent-stem		Grass Symons			Minimum	Maximum		
Depth of thermometer	4 inches	8 inches	4 inches	8 inches	1 foot	1 foot	4 feet	°C	°C	°C	*centimetres*
24-hour period ending 0900 GMT on	*degrees Celsius*				*degrees Celsius*						
21st	−0.4	+0.1	0.0	0.0	0.0	0.0	0.0*	−3.0	−0.5	−5.2	14
22nd	−0.7	−0.5	−0.9	−0.5	−0.2	−0.3	−0.1*	−7.1	−0.5	−12.3	14
23rd	−0.9	−0.7	−0.8	−0.6	−0.4	−0.5	0.0*	−12.1	−0.4	−15.8	13
24th	+0.6	−0.2	0.0	−0.1	−0.3	−0.2	−0.1*	−10.7	−2.3	−12.0	13
25th	+0.1	+0.4	+0.5	+0.4	+0.2	+0.2	−0.1*	−10.3	−4.3	−9.3	12
26th	+0.2	−0.2	−0.2	−0.4	−0.4	−0.2	0.0*	−10.3	+0.1	−12.6	12
27th	+1.8	+1.4	+1.9	+1.3	+0.8	+0.9	−0.2*	−0.6	+7.4	−0.6	6
28th	+0.4*	+0.4	+0.7*	+0.7*	+0.2	+0.3	0.0*	+1.7	+3.9	+0.1	0
Temperature at 0900 GMT on 28th in °C	0.3	−0.1	0.3	0.2	−0.2	−0.1	3.9				

*Final temperature was above freezing-point; with all other changes the final temperature was below freezing-point.
**Measurement taken on snow surface when snow was lying and thermometer kept free of snow if possible (see Observer's Handbook[81]).

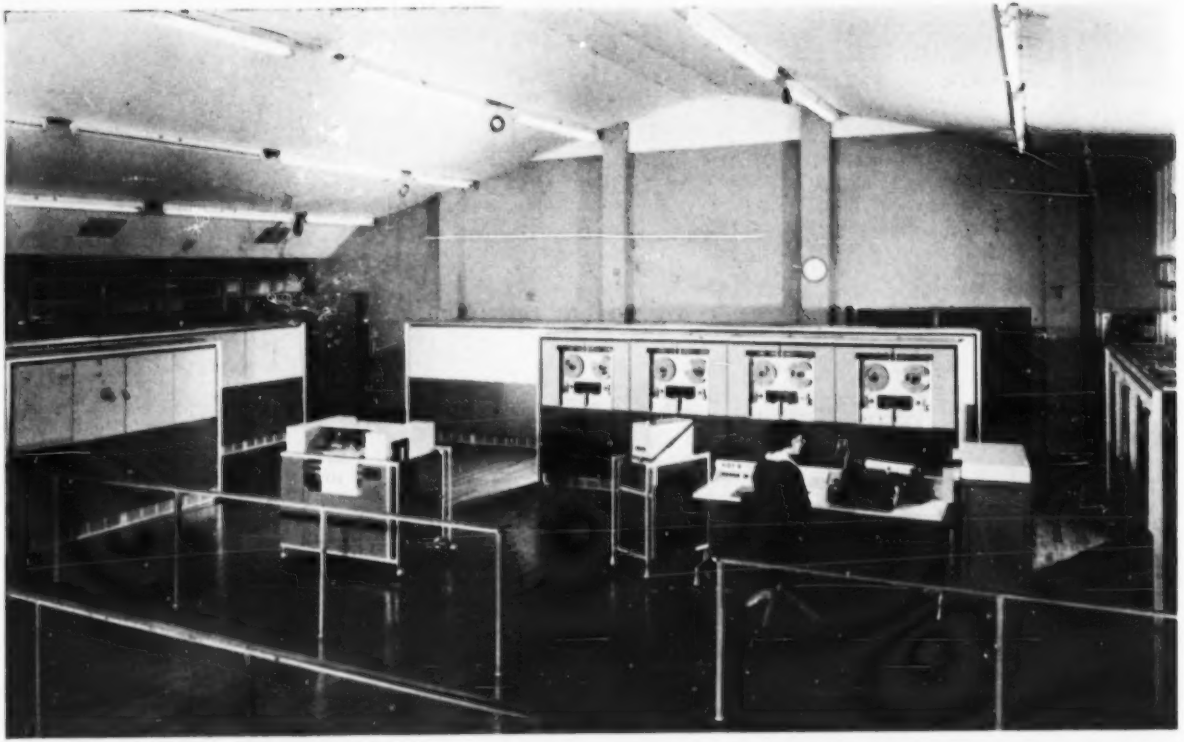

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PLATE I—PART OF THE KDF 9 INSTALLATION IN THE ENGLISH ELECTRIC-LEO BUREAU AT KIDSGROVE

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To face p. 16

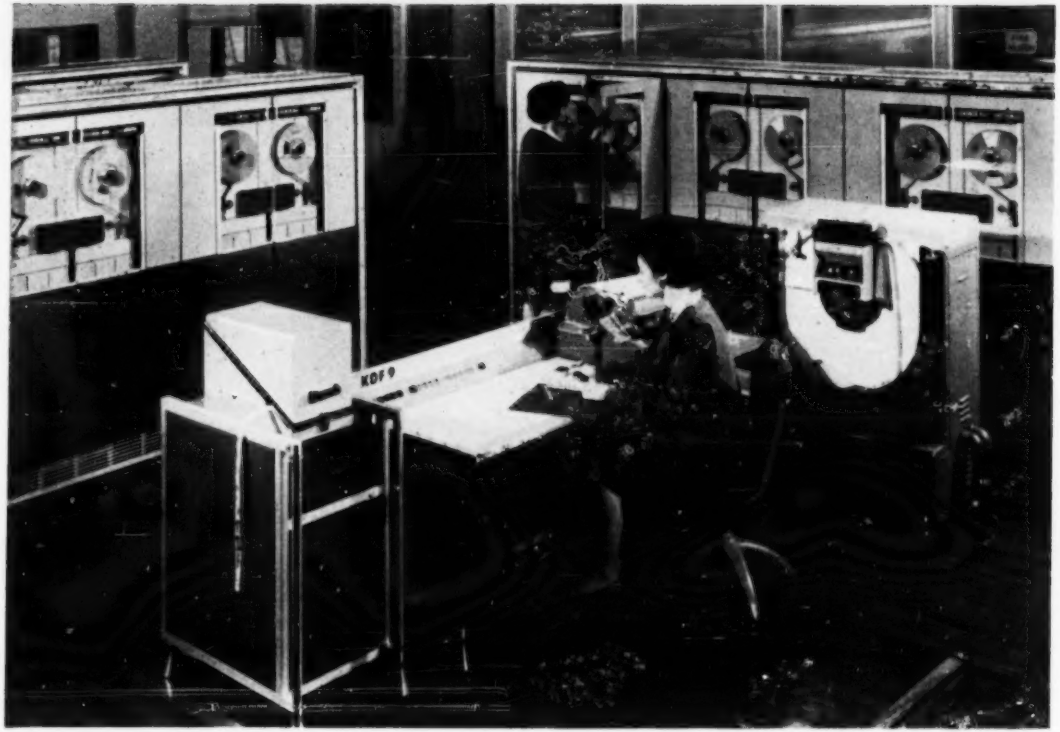

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PLATE II—PAPER TAPE PUNCH, CONTROL CONSOLE, AND PAPER TAPE READER OF THE KDF 9

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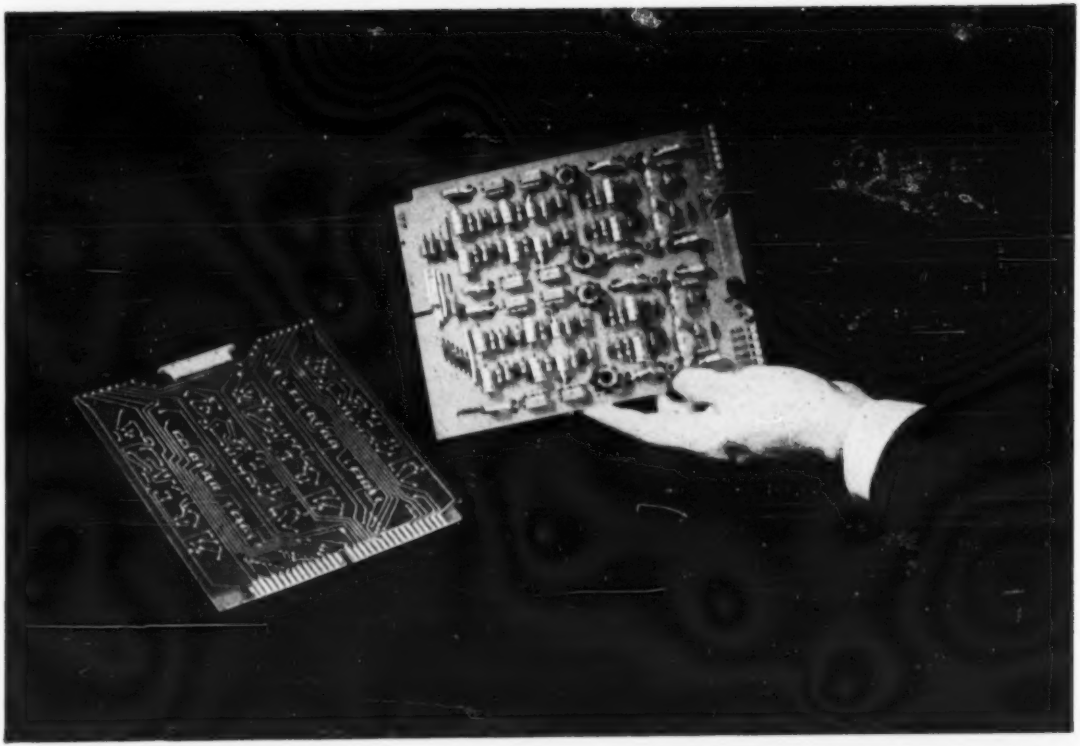

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PLATE III—'PULSE AMPLIFIER' PRINTED CIRCUIT PLUG-IN MODULE OF THE KDF 9

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To face p. 17

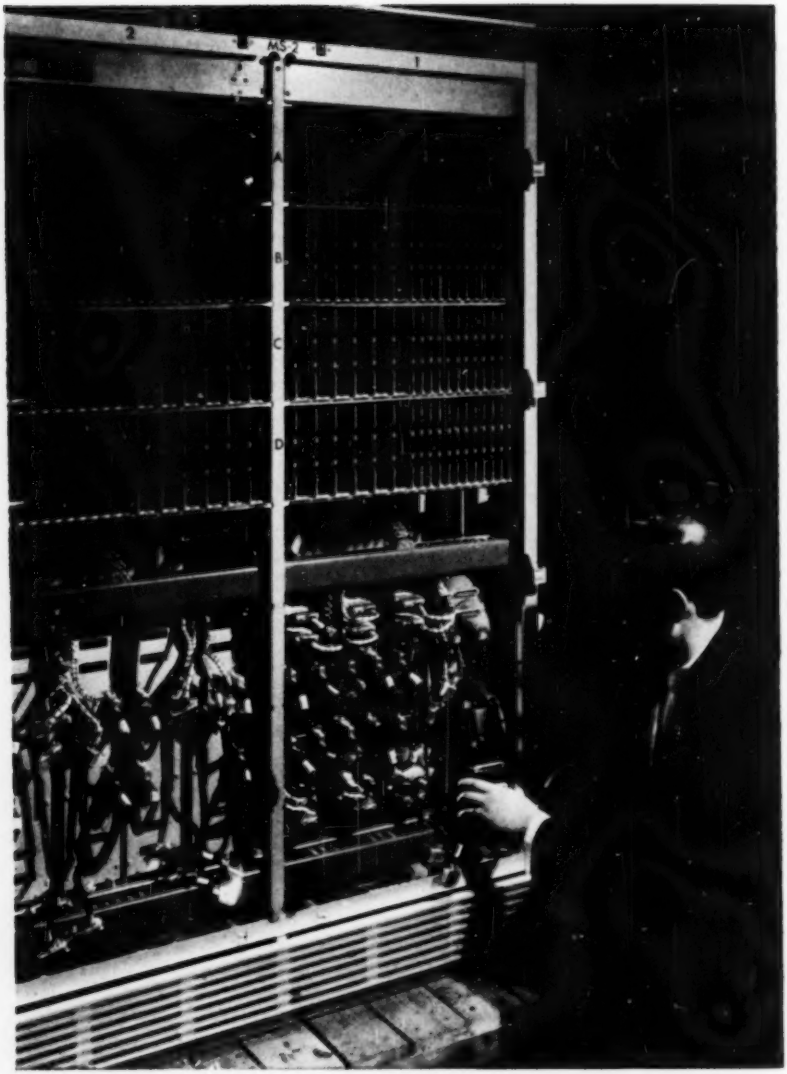

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PLATE IV—ONE OF THE MAIN STORE RACKS OF THE KDF 9 SHOWING CORE MODULE BEING FITTED

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TABLE III—CHANGES IN SOIL TEMPERATURE AT VARIOUS DEPTHS IN LATE JANUARY 1963, WITH ASSOCIATED AIR TEMPERATURES AND SNOW DEPTHS—*continued*

(*c*) ROTHAMSTED EXPERIMENTAL STATION

Type of soil cover	Bare soil			Grass				Air screen temperature				**Grass thermometer temperature: overnight minimum		Snow depth at 0900 GMT at end of period	
Type of thermometer	Bent-stem		Symons	Bent-stem		Symons		Minimum		Maximum					
Depth of thermometer	4 inches	8 inches	1 foot	4 inches	8 inches	1 foot	2 feet	4 feet									
24-hour period ending 0900 GMT on	*degrees Fahrenheit*								°F	°C	°F	°C	°F	°C	*inches*	*centimetres*
21st	−0.1°	+0.1°	+0.2°	+0.6°	0.0°	0.0°	−0.1°	0.0°	23	−5.0	29	−1.7	20	6.7	7	18
22nd	−0.4°	0.0°	−0.1°	−0.6°	0.0°	−0.1°	−0.2°	−0.1°	12	−11.1	27	−2.8	16	−8.9	6	15
23rd	0.0°	−0.2°	−0.5°	−1.2	0.0°	+0.1°	−0.1°	0.0°	2	−16.7	27	−2.8	13	−10.6	6	15
24th	−0.7	0.0°	−0.1°	0.0	−0.7°	−0.5°	−0.3°	−0.1°	4	−15.6	27	−2.8	12	−11.1	5	13
25th	−0.6	−0.1°	+0.1°	−0.4	−0.2°	−0.2°	0.0°	−0.1°	7	−13.9	23	−5.0	13	−10.6	5	13
26th	+0.8	−0.1°	0.0°	+0.5	0.0°	−0.1°	−0.2°	0.0°	7	−13.9	33	+0.6	13	−10.6	4	10
27th	+0.1°	0.0°	0.0°	+1.0°	−0.3	+0.1°	+0.1°	−0.2°	31	−0.6	40	+4.4	29	−1.7	2	5
28th	0.0°	+0.1°	−0.1°	−0.1	+0.6°	+0.1°	+0.1	−0.2°	33	+0.6	36	+2.2	31	−0.5	2	5
Temperature at 0900 GMT on 28th in °F	32.1	32.9	32.9	32.0	32.4	33.4	36.2	39.4								
°C	0.1	0.5	0.5	0.0	0.2	0.8	2.3	4.1								

(*d*) CARDINGTON

Type of soil cover	Grass					Air screen temperature		**Grass thermometer temperature: overnight minimum	Snow depth at 0900 GMT at end of period
Type of thermometer	Bent-stem			Symons		Minimum	Maximum		
Depth of thermometer	2 inches	4 inches	8 inches	1 foot	4 feet				
24-hour period ending 0900 GMT on	*degrees Celsius*					°C	°C	°C	*centimetres*
21st	−0.2	−0.2	+0.2	0.0°	0.0°	−7.2	−1.1	−10.8	15
22nd	−1.0	−0.7	−0.2	0.0°	0.0°	−17.1	−1.9	−20.3	15
23rd	0.0	−0.1	−0.2	−0.1°	−0.1°	−16.1	−2.8	−20.4	15
24th	−0.6	−0.8	0.0	−0.1°	−0.1°	−18.3	−6.2	−19.2	15
25th	+0.7	+0.8	−0.2	−0.1°	0.0°	−12.4	−5.9	−11.4	15
26th	+0.6	+0.2	+0.1	0.0°	−0.1°	−11.9	+0.6	−13.9	13
27th	+1.3	+1.1	+0.3	0.0°	−0.1°	−0.9	+5.1	−0.2	5
28th	+0.2	+0.2	+0.1	0.0°	−0.1°	+1.4	+3.2	+0.6	1
Temperature at 0900 GMT on 28th in °C	−0.1	−0.3	−0.3	0.1	3.5				

*Final temperature was above freezing-point; with all other changes the final temperature was at or below freezing-point.
**Measurement taken on snow surface when snow was lying and thermometer kept free of snow if possible (see Observer's Handbook[21]).

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551.501.4:681.14

A NEW COMPUTER SYSTEM FOR THE METEOROLOGICAL OFFICE

By E. J. SUMNER, B.A.

Introduction.—The first Meteorological Office (MO) computer was delivered in the autumn of 1958 and became known in the office as METEOR. It was a *Ferranti Mercury* type, based on thermionic valves and operating solely from punched paper tape. It soon became evident that METEOR, although a very powerful tool for research as it was primarily intended to be, was not going to be fast enough or reliable enough for work that had to be carried out unfailingly to a tight schedule—operational numerical weather prediction, for example, employing the latest multi-layer, larger-area models of the atmosphere. Moreover it had neither the external facilities nor the control features necessary to undertake the data handling required in modern climatological services or in the automatic editing of telecommunication messages.

During recent years enormous strides have been made in computer manufacture which is now universally based on transistors and other improved components mounted on printed plug-in circuit boards. The improved manufacturing techniques have made it possible to construct faster, more complex, more versatile, and at the same time more compact and more reliable machines, controlling a large number of ancillary devices—entire electronic data-processing *systems*, in fact. The one chosen as a replacement for METEOR is the *English Electric-Leo* KDF 9 computer system which is to be installed in the meteorological headquarters, Bracknell, in the autumn of 1964, and will be called COMET.

This article describes the new system and, very briefly, the associated services that will be available to all branches of the Office. The reader is referred to a previous paper[1] for the background.

The general system.—Photographs of a typical KDF 9 installation are shown in Plates I and II. On view in the first plate are: a paper tape reader and punch (to the right and left of the operator's console, respectively), several magnetic tape units (immediately facing the operator), a line-printer (left foreground) and, in the background, various cabinets of the computer itself. The close-up on Plate II shows more details of the tape units and of the console, including the automatic typewriter for communication between the computer and the operator.

The storage capacity, operating speeds and ancillary equipment of the new Meteorological Office system are listed in Table I, side by side with comparative information for METEOR. KDF 9 is in all respects faster than METEOR, with a larger memory store and a wider range of input/output devices and operating media. Like all computers of its generation, it is built on a 'modular' or 'packaged' principle so that the number of external devices and the size of the internal memory can be increased later, within limits, with little interference with normal working.

Plate III shows back and front views of a typical printed circuit module, one of a hundred or so basic circuits from which the computer is assembled. The one in question is used to amplify the information pulses that pass to and fro within the computer. In Plate IV a memory unit is being fitted below racks of circuit boards.

The components of circuit modules are intrinsically very reliable but if one fails, the maintenance engineer, assisted by special diagnostic programmes and test equipment, has the relatively easy task of finding the module affected. A spare one can then be plugged in and the computer is ready for use again, while the faulty board is repaired at leisure.

As mentioned above, KDF 9 is faster than METEOR—it has a basic rhythm of 6 microseconds, that is ten times faster. However, for arithmetical processes, speeds are up by a larger factor (e.g. by a hundred for division) and so are magnetic tape reading and writing speeds, although for the other input/output devices the speed increases are only of the order of three to six times. Carrying out a full 'numerical prediction' run on METEOR takes 4 hours at present; it is estimated that this could be done in less than 20 minutes on KDF 9. However, in assessing the increased capacity for work of the new system as compared with the old, speed is not the only factor. There is also the increased reliability and the more efficient utilization arising from the fact that up to four different programmes may be run simultaneously on KDF 9 (see the section on time sharing, later). All things considered, its capacity for work will be of the order of twenty times that of METEOR.

Physically KDF9 is very little larger and the heat dissipation is only about half. However the air-conditioning requirements are much more stringent; dust and humidity control, as well as temperature control will have to be provided.

Operating media.—Whereas data from the meteorological library of some 30 million punched cards can only be made available to METEOR via

TABLE I—KDF9 AND METEOR COMPARED

ITEM	KDF 9		METEOR	
Internal storage				
Main store	12,288 48-bit words		1024 40-bit words	
Magnetic drum	40,960 48-bit words		16,384 40-bit words	
Operating speeds	*microseconds*		*microseconds*	
Access to main store	2–12 (average 7)		120	
Addition and subtraction—fixed-point*	1		–	
floating-point	7–12		180**	
Multiplication—fixed-point	15		–	
floating-point	15–19		300**	
Division—fixed- and floating-point	35–40		3800	
Input/output equipment	Number	Speed	Number	Speed
Paper tape readers	3	1000 characters per second	1	300 characters per second
Paper tape punches	3	110 characters per second	1	33 characters per second
Card readers	1	600 cards per minute	0	
Line printers	1	1000 lines per minute (160 characters per line)	1	150 lines per minute (92 characters per line)
Magnetic tape units	6	40,000 characters per second	0	

*See section on information representation for explanation of fixed- and floating-point.
**Note: Arithmetic times on METEOR include the time of one transfer from the main store to the arithmetic unit, whereas those for KDF 9 do not.

special machines which first convert them to paper tape, KDF 9 will be capable of reading punched cards directly, at 600 cards per minute. Paper tape facilities are also provided, more abundantly in fact because so much more teleprinter data on tape will be handled in future, and because of the increased local production of punched tape (e.g. from digitizing equipment such as that installed at Kew Observatory to record radiation data). Both 5- and 8-channel tape, with different codes, will be in use, requiring that readers and punches should be quickly switchable from one mode to the other, as required.

For the first time, the MO will be equipped to deal with data recorded on magnetic tape, a most powerful medium in view of its high storage capacity (several hundred times that of cards) and its extremely high reading and recording speeds, viz. 40,000 characters (decimal or alphabetical) per second. A single reel of $\frac{3}{4}$-inch tape, 2400 feet long and about 10 inches in diameter, will hold more than 10 million characters, doubly recorded for reliability in binary code, in two 8-channel sets side by side. On input to the computer from magnetic tape, both copies of the data are scanned simultaneously; if either or both give a valid response the correct character is transferred into the main computer store. Double recording eliminates the more usual failure caused by a very local blemish on the tape or a particle of dust interposing itself between the reading head and the tape and affecting only a single channel.

Finally, there is the fast printer operating at 1000 lines per minute, each line containing up to 160 characters. This will have good registration so that results may be printed onto stationery on which map outlines or special lined formats have been pre-printed. Multiple copies may also be obtained by the usual methods.

The information representation and memory stores.—Numbers are stored within the memory of the computer as groups of 48 bits (binary digits), each group constituting a 'word' or 'register.' The number may be either in fixed-point or floating-point form. Briefly, in fixed-point arithmetic the programmer has to remember where the decimal point comes in the number whereas in floating-point this is automatically taken care of by the computer,* but the price paid for this facility is slower working, especially for addition and subtraction. The floating-point representation also permits larger numbers to be handled, although with less precision.

Decimal or alphabetical characters are entered on tape in a 6-bit code and are therefore stored within the computer eight to a 'word.' Instructions on the other hand are made up of 8-bit 'syllables,' six to a 'word.' Some instructions (e.g. all of the arithmetic instructions) are only one-syllable; others are two or three (maximum). Whatever their length, they are strung together in the store in strict succession, overflowing from one register to the next if necessary. This makes for great economy of storage of programmes within the computer.

The MO computer will have three 4096-'word' modules of main storage, which can be expanded later to a maximum of eight (i.e. 32,768 'words') if required. Access to any 48-bit 'word,' containing data or instructions, in this store can be obtained in 12 microseconds, frequently less. Before arithmetic and other operations can be carried out on numbers in the main store, they have

*Numbers in floating-point are considered to be in the form $m \times 2^n$ and the m and n are separately stored, 40 'bits' of a 'word' being reserved for the former and 8 for the latter.

first to be transferred to a special 'nesting' store of only 16 'words.' There are four such stores, one reserved for each possible programme. The stores operate on a 'first-in-last-out' principle, i.e. 'words' are inserted very much like the bullets in a rifle magazine, but the top three 'words' (or cells) may be rearranged cyclically. Once 'words' or numbers are in the nesting store, a variety of arithmetical and manipulative processes may be carried out on them at very high speed—often within 1–2 microseconds—without further (slower) reference to the main store. This mode of working is particularly efficient when repeated iterations on the same numbers have to be carried out, e.g. in evaluating a polynomial.

Another novel feature of KDF 9, conducive to faster working, is an 'advanced think' control unit by means of which transfers between the main and nesting stores take place in parallel with computing, whenever this can be arranged by the central control of the computer. In favourable circumstances access times to the main store may be effectively shortened from 12 to 2 microseconds (on average, to 7 microseconds).

Yet another store, which however is more of an external device than an internal memory, is the magnetic drum, capable of holding 40 'bands' each containing 1024 'words' of information. The drum rotates at about 3,000 rev/min, and access to each band takes about 10 *milliseconds* which is very slow by comparison with the maximum time of 12 *microseconds* quoted for access to the main store. However, if a long string of data is required in exactly the sequence it is stored on the drum, a continuous transfer rate to the main store (to which information must be transferred before use) of the order of half a million characters per second can be achieved.

Programming.—Instructions to the computer must be written out in a suitable language. The principal KDF9 programming language is called *User Code*; it is fairly self-evident in form and therefore easy to remember. For example, fixed-point arithmetic functions employ the usual mathematical symbols (+, −, ×, ÷), and floating-point is distinguished merely by the addition of the letter F. Thus ×F; means: 'multiply two floating-point numbers in the top two cells of the nesting store together and store the result in the top cell.' (The semi-colon is written after *every* instruction as a terminator.)

Plain-language instructions like ERASE;, FINISH;, ZERO; and NEG; (negative) are used as well as equally obvious but more technical words such as DUP;, ROUND;, PERM;, AND;, OR; and NOT;. Then there is a host of instructions represented by initial letters, such as PR; or PW; (*paper tape read* or *write*, respectively), MRWD; (*magnetic tape rewind*), MBR; (*magnetic tape backward read*), LP; (*operate line printer*), etc.

Usually instructions are carried out in strict sequence, as they are written, but from time to time it is necessary to jump to some remote point in the programme depending on some criterion, e.g. whether a particular value is positive, negative or zero. For example, there is the instruction Jr≥Z; which is interpreted as: 'jump to the point in the programme labelled "r" (an integer) if the top cell of the nesting store is greater than or equal to zero, otherwise proceed to the next instruction in sequence.'

Obtaining access to data stored in the main store is particularly easy on KDF 9. Each main-store register must carry an 'address' to identify it. In one form of addressing, data registers are designated Y0, Y1, Y2,....etc. The

instruction Yr; brings the word in main-store register r to the top cell of the nesting store (pushing all the other words in the nesting store down, one cell). The instruction =Yr; transfers the word from the nesting store to the appropriate main-store register.

Thus in order to add together two floating-point numbers in the main-store locations Y1 and Y2 and store the result in Y3, say, the programmer simply writes:

Y1; Y2; (the two numbers are now in the top two cells of the nesting store) +F; = Y3; (the result is now stored away).

To form the fourth power of the product of these same two numbers, say, the instructions are:

Y1; Y2; ×F; DUP; ×F; DUP; ×F; = Y3;.

The first multiplication forms the product in the top cell of the nesting store. Then a copy of this is made in the second cell by means of the DUP; instruction. The second multiplication then forms the square. Because of the next DUP; this square is copied and the final multiplication gives the fourth power.

Programmes have to be punched character by character onto paper tape and then read into the computer under the control of a special translator or 'compiler' programme which carries out a conversion to the internal machine codes. (For various reasons the internal codes are quite different from those on tape.)

Apart from User Code there are several other programme languages which are even simpler. These include *Fortran* and *Algol* (algebraical languages), *Cobol* (almost basic English) and *Mercury Autocode*, which will be familiar to many users of METEOR. Programmes written in these languages will be shorter and easier to get right but will generally use the computer less efficiently. They make more concessions to the programmer and are more remote from the internal codes and mode of functioning than User Code. The translation process is thus more complex and the compiled programme (either on paper or magnetic tape), which is the one actually used at 'run time,' will usually take up more internal storage and use up more computer time.

It will therefore be politic to write programmes that have to be run many times in User Code whereas those intended for one-off jobs (e.g. answering a specific climatological inquiry) would be more expeditiously dealt with in one of the other languages. The choice of language depends on the sort of problem to be dealt with (Cobol, for example, is more adapted to business applications), although the personal background and taste of the programmer is not entirely to be discounted.

Parallel processing and time sharing.—One feature of electronic computers has always been the great disparity between the speeds at which they can accept information into the main store and the much lower speeds of peripheral devices (printers, readers, punches, etc.). This disparity has inevitably led to development of techniques for carrying out several input/output operations in parallel with each other and with internal processing operations.

KDF 9 is capable of operating up to 16 peripheral units simultaneously, subject only to a maximum combined transfer rate of $1\frac{1}{3}$ million characters per second. All the units of the MO system can in fact be in operation at one

time without saturating the input/output control. Transfers can be in sizable data blocks and, once initiated, proceed to completion quite independently of central control which can be devoted to processing data already in the nesting store.

It is seldom however that any one programme will need all 16 peripheral units to itself, or can be written so as to keep central control busy all the time. Thus, provision is made for the computer to share its time between several programmes. The order of priority of time-shared programmes has to be laid down. The first-priority programme proceeds without interruption until it is held up because it needs to read in further data or print out intermediate results, say, or even because of a fault in one of the units it is using. In this event a second programme is automatically switched in until the first is ready to resume control or until it is itself held up for one reason or another, whereupon control passes to a possible third programme, and so on up to a maximum of four. While a particular programme is being dealt with, input/output transfers relevant to that and the other programmes may be proceeding quite independently, as previously explained.

The internal switching and general 'house-keeping' of all these activities is under the control of a master programme called the 'Time-sharing Director.' The programmer need not be concerned with this: he merely writes his programme as though it were the only one present. Information as to the memory and peripheral unit requirements of each programme has, of course, to be supplied to the console operator who has to ensure that the total requirements do not exceed those available to the system at the time.

The aim is to keep all internal circuitry and all ancillary devices as busy as possible in the interest of economy, although this may mean some sacrifice in the speed of execution of particular programmes. However if programmes are judiciously combined, e.g. if a heavy computing programme is run with one requiring a simple transfer, say, from tape to printer, then the hold up to either will be quite insignificant.

Final remarks.—KDF 9 will greatly increase the computing and data processing facilities available within the Office. It will introduce a new quality into the work of research and service branches alike, and make great demands on both. Added powers almost invariably bring added problems and responsibilities.

The actual day-to-day running and maintenance of so large and so sophisticated a system on a time-sharing basis will be quite a task in itself. So too will be the production and organization of the large ever-growing library of programmes and data, recorded in a variety of media, that will be required to feed it.

MO18c will be largely responsible for this as a central service and will also provide programming assistance on request. The more specialized programming of some research problems will, however, continue to be done by the branches concerned. Processing via conventional punched-card machines will probably diminish, although for smaller jobs it will be many years before they will be entirely superseded.

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551.510.536:550.383:533.7

THE NATURE OF THE EARTH'S OUTER ATMOSPHERE (THE MAGNETOSPHERE) AND ITS POSSIBLE INFLUENCES ON METEOROLOGY

By F. D. STACEY, B.Sc., Ph.D.

Introduction—the magnetosphere.—The study of the very high atmosphere is now recognized as relevant to meteorology. Although at the present time the direct influences upon our weather of effects in the remote atmosphere appear mostly marginal or uncertain, this is probably due more to ignorance than to a lack of real connexions. Consequently the level to which meteorological research interests extend is continually rising and it is pertinent to consider whether we can really assign any upper limit to the atmosphere. The atmosphere is most satisfactorily defined as that gaseous envelope which travels with the earth in its orbit around the sun. Thus defined, the atmosphere extends to between 5 and 20 earth radii and is therefore very much more extensive than that considered in normal meteorology. By far the largest part of it consists of a tenuous, ionized gas or plasma, whose behaviour is directly controlled by the earth's magnetic field. For this reason it has been termed 'the magnetosphere' (Gold[1]).

At first sight it might appear that the geomagnetic field, being approximately dipolar, extends outwards into the interplanetary medium indefinitely, with strength decreasing as the cube of the distance from the earth, but this cannot be so. The field rotates with the earth and the electrically conducting plasma is carried around with it, because the currents induced in any plasma, which does not initially rotate with the field, would very rapidly compel it to do so. But the whole of interplanetary space cannot be rotating with the earth; the field at great distances would be too weak. Instead the more remote plasma prevents the penetration of the rotating field. The field itself is thus restricted to a limited volume (the magnetosphere), within which the plasma moves with the earth, and beyond which the field does not penetrate and the plasma moves independently of the earth. The geomagnetic field thus provides a giant magnetic bottle for the atmosphere and substantially isolates it from the interplanetary medium.

Effect of the 'solar wind.'—The emission by the sun of a more or less uniform stream of protons and electrons constitutes the 'solar wind,' which is continually 'blowing' past the earth. We may think of the wind as a moving plasma which tends to carry the earth's field with it, so that the magnetosphere is compressed on the sunlit side and extended on the dark side. The solar wind deforms the magnetospheric surface very much in the way one might expect an ordinary atmospheric wind to deform a flimsy balloon suspended from a fixed point in its interior by elastic bands to the surface. This is indicated in Figure 1, which is a diagrammatic representation of the internal structure of the magnetosphere. The general picture has now been established by satellite research, although many details are still not clear. An alternative approach to the problem of magnetospheric compression by the solar wind is to consider the motion of individual solar-wind particles approaching the earth. As they strike the magnetic field, protons are deflected one way and electrons the other. This charge separation constitutes an electric current in the magnetospheric surface, which has just such a magnitude and configuration as to cancel the field outside the surface. The probable structure of the magnetospheric surface is then more

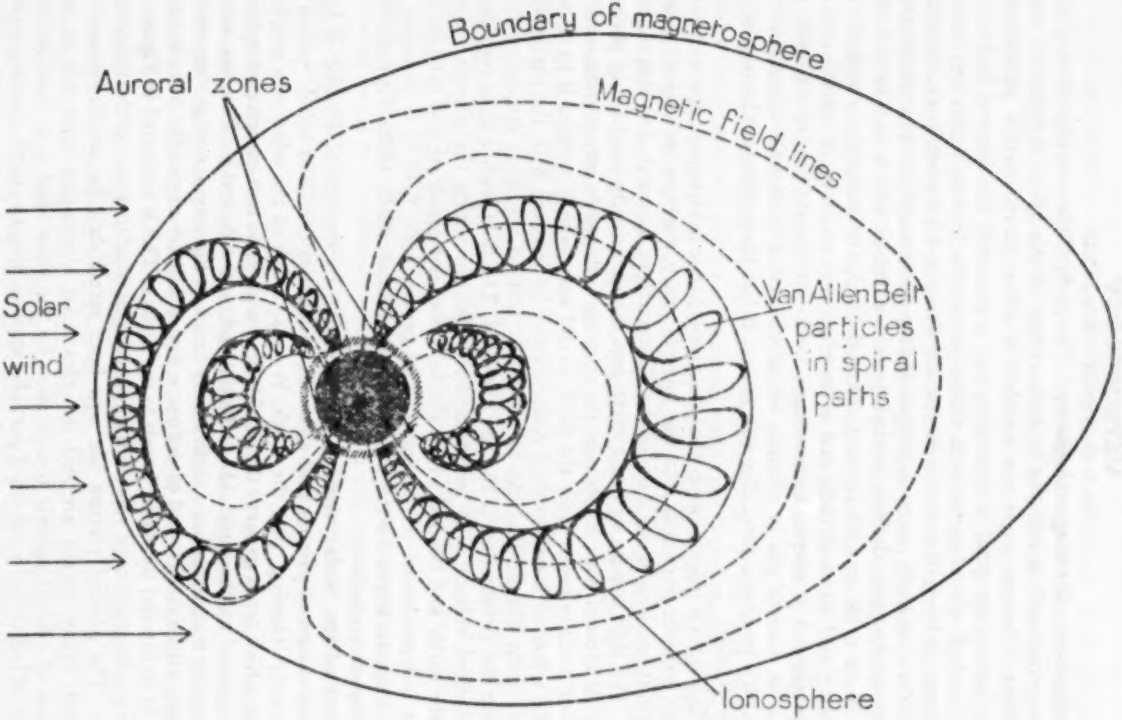

FIGURE 1—THE MAGNETOSPHERE

obvious because not all of the particles have the same initial momentum and they therefore penetrate the surface to different depths. For this reason the magnetospheric boundary is actually a transitional zone several hundred kilometres thick, in which there is a momentum exchange between the magnetospheric and interplanetary plasmas. Axford and Hines[2] have pointed out that this momentum exchange is equivalent to a frictional contact between the solar wind and the magnetospheric plasma, driving an internal convective motion of the magnetosphere with important consequences. Fejer[3] considers that rotation of the field within the magnetospheric boundary, as deformed by the solar wind, may constitute at least as important a driving mechanism for convection. Whatever its precise cause, the convection induces magnetospheric currents which are responsible for the regular diurnal geomagnetic variations and are most noticeable in the auroral zones where particularly intense currents flow at ionospheric heights.

The radiation belts.—Extensive regions within the magnetosphere contain intense fluxes of energetic particles whose velocities are such that they are 'trapped' by the magnetic field. They are commonly known by the name of their principal discoverer, J. A. Van Allen, and are disposed in the manner indicated in Figure 1. The development of our knowledge, particularly of the outer of the two main belts has been reviewed recently by Farley.[4]

We are still a long way short of a satisfactory detailed explanation for the origin and structure of the Van Allen belts but the elementary mechanical explanation of particle trapping is straightforward. The velocity of any particle may be resolved into two components, parallel and perpendicular to the magnetic field lines. The component along the field is unaffected by it but the perpendicular component is deflected so that the particle spirals about the field lines. Very energetic (cosmic ray) particles are only slightly deflected by the field; very low-energy particles are confined by the field to so small a space that they can be regarded as stationary (except when they are impelled by electric fields set up by the magnetospheric convection). Particles of moderate energy (important energies appear to be 0.1–1 mega electron-volt (MeV) for electrons, 0.5–5 MeV for protons) have spiral paths small compared with the size of the magnetosphere but are nevertheless sufficiently energetic to ignore (almost) the convective or tidal motions. They spiral about the magnetic field lines with the parallel component of their motion carrying them towards one of the auroral zones. As the field lines approach the earth they converge and this has two effects upon the particle motion, as shown in Figure 2. The spirals

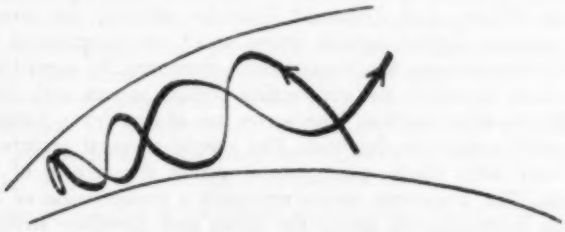

FIGURE 2—PATH OF A VAN ALLEN BELT PARTICLE REFLECTED FROM AN AURORAL ZONE BY CONVERGENCE OF THE MAGNETIC FIELD

become tighter in the stronger field and the parallel component of the motion is reversed by the convergence of the field lines. The particles are magnetically reflected from the auroral zones at each end of their paths.

Particles of both signs have superimposed drift motions, eastwards for electrons and westwards for protons, which constitute a 'ring current' (at a distance of several earth radii) whose strength changes substantially during magnetic storms, (Akasofu and Chapman[5]).

Geomagnetic storms.—At irregular intervals the sun ejects streams of charged particles with much higher velocities than those of the normal solar wind. The arrival of one of these streams at the magnetospheric surface is noticeable almost immediately in the records of magnetic observatories as a 'sudden commencement.' This is so called because it is a normal (although not necessary) precursor to a magnetic storm and because its suddenness in a previously 'quiet' record can be quite striking. A magnetogram or a record of a storm normally has a form which is represented somewhat diagrammatically in Figure 3, but wide ranges of variation are possible, depending upon the sequence of particle fluxes which reach the earth and the initial state of the magnetosphere.

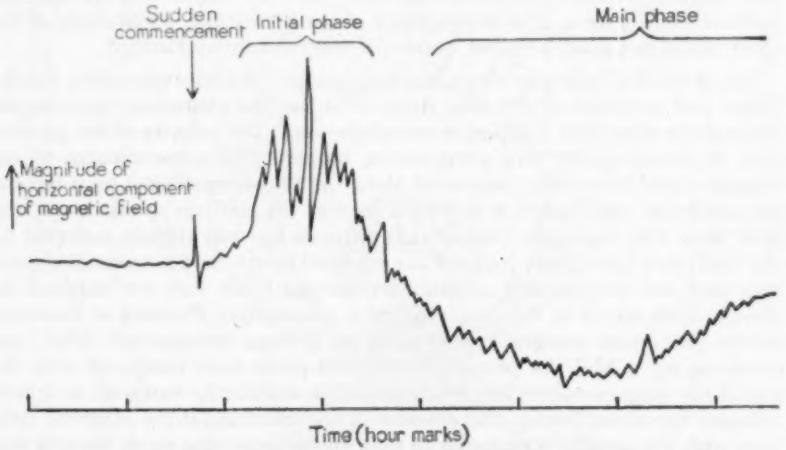

FIGURE 3—CHARACTERISTIC SEQUENCE OF CHANGES IN FIELD DURING A MAGNETIC STORM

The sudden commencement mechanism has been explained most satisfactorily by Wilson and Sugiura.[6] Particles striking the magnetospheric boundary generate hydromagnetic waves which are propagated to the earth as magnetic disturbances. Hydromagnetic waves may be regarded as electromagnetic waves in which the conducting plasma moves with the field lines and controls the wave motion. The waves are of two types, longitudinal and transverse with respect to the field. The simple classical picture of tubes of magnetic force with elastic properties describes the nature of these waves quite clearly. The transverse waves represent a compression of the tubes of force, which is propagated across the tubes and therefore strikes the earth principally in low latitudes where the geomagnetic field is nearly horizontal. The longitudinal waves may be regarded as 'kinks' which propagate along the tubes to high latitudes.

Following the sudden commencement of a magnetic storm there is normally an initial phase, lasting an hour or so, during which the field intensity at the earth's surface is increased by the continued compression of the magnetosphere. This is followed by a day or so of 'main phase' during which an enhancement of the ring current reduces the field at the surface. A well developed main phase is commonly accompanied by auroral displays at high latitudes. The connexion between aurorae and the ring current is readily understood although the mechanism has not been conclusively demonstrated. In magnetically disturbed conditions solar particles probably penetrate to the outer Van Allen belt where the increased particle density causes enhancement of the ring current. However, either the higher particle density is unstable or else the new particles have velocities unsuitable for permanent trapping. Some of the particles are 'dumped' into the ionosphere in the auroral zones, where the outer belt is terminated, and cause auroral displays.

Space science and meteorology.—The action of the geomagnetic field in directing particles towards high latitudes may apply to fine particulate matter, as well as to the protons and electrons of the Van Allen belts. Solid particles of diameter 100 ångström units (Å) approaching the earth with velocities of the order 10 km/sec and positively charged to about 10 volts by the photoelectric emission of electrons in the sun's ultra-violet and X-radiation, would have spiral paths of dimensions appreciably smaller than the magnetosphere and they would therefore spiral towards high latitudes. Larger particles behave similarly if they are more highly charged or approach the earth more slowly. Thus a significant proportion of the meteoritic dust reaching the lower atmosphere probably does so quite non-uniformly. Its subsequent redistribution therefore depends upon the circulation in the denser part of the atmosphere. If the ice nuclei necessary for rainfall depend for their formation at least partly upon the arrival of meteoritic dust, as Bowen[7] has been asserting for a number of years, then it would follow that rainfall is directly influenced by magnetospheric processes.

The suggestion that meteoritic dust is magnetically directed towards high latitudes may be relevant to the recent discovery by Hemenway *et al.*[8] that a noctilucent cloud, sampled by a rocket flight over Sweden, contained particles of nickel-iron in the size range 500Å–5000Å. Noctilucent clouds are observed at high latitudes in summer months, when the sun is below the horizon but sufficiently near to it to illuminate the clouds. They occur at very much higher altitudes (75 km in the Swedish observations) than normal clouds; so high that it is doubtful whether ordinary atmospheric moisture could be responsible. The nickel-iron composition is very suggestive indeed of meteoritic origin, since metallic nickel-iron is one of the important constituents of meteorites. It is therefore most reasonable to regard the noctilucent cloud material as meteoritic dust which has been precipitated through the magnetosphere. However, magnetic direction of particles in this size range requires that they be charged to several thousand volts. Secondary electron emission during bombardment by electrons of the inner Van Allen belt appears to be the most plausible mechanism for producing a charge with this potential.

The problem of moisture in noctilucent clouds still arises because the collected cloud particles appear to have had ice coatings. In contemplating the moisture content of the outer atmosphere it may be necessary to consider the exchange

of hydrogen with interplanetary space, and in particular the precipitation of protons by the solar wind. It is interesting (but possibly not significant) to note that a solar wind of 5×10^9 protons/cm^2 sec (a figure obtained from Bierman's[9] deduction from the behaviour of comet tails) arriving at a hemispherical magnetospheric surface of radius 10 earth radii would, if entirely collected by the earth, accumulate in the whole of geological time to produce a volume of water approximately equal to that of the oceans.

Discussion of the role in meteorology of meteoritic matter has been renewed recently, particularly by Bowen,[10] Adderley[11] and Bigg.[12,13] Variations with lunar phase of rainfall, ice nucleus concentrations, ozone and geomagnetic storms are connected by strong implication with a lunar control on meteor arrival. If any or all of these correlations are real they may depend upon a modulation by the lunar gravitational field, of the interplanetary dust arriving at the earth, electric and magnetic effects being almost certainly much too small. Even so, it requires that the velocity of the dust relative to the earth–moon system be very small, in order that lunar gravity should be able to influence the orbits of dust particles sufficiently. In fact the particles must be in orbits around the sun, not very far removed from that of the earth.

A recent meteorological discovery which has attracted a good deal of attention from geophysicists concerned with problems of the very high atmosphere, is the 26-month cycle in equatorial stratospheric winds, discussed in detail by Veryard and Ebdon.[14] Available measurements indicate that the meridional winds reverse simultaneously all the way round the equator. The occurrence of a westerly wind of 20 knots or so, encircling the equator is not easily explained because it constitutes an air mass rotating faster than the earth, in the zone of the earth's maximum angular momentum. Stacey and Westcott[15] considered the possibility that the stratospheric air mass had been brought downwards by a vertical wind from ionospheric heights at which its electrical conductivity may have compelled it to rotate with the geomagnetic field. Such a mechanism allows the generation of a westerly wind by a simple conservation of angular momentum, but it requires a rather improbably strong vertical wind in the ionosphere. Nevertheless, Funk and Garnham[16] have reported a cycle of similar period in Australian ozone data, the phase coinciding very convincingly with that of the stratospheric wind if it is assumed that the westerly wind is in phase with the downward wind and that ozone is accumulated at lower than average altitudes by the downward wind and lags in phase by a quarter cycle, that is it represents an integration of the vertical wind. The implication that the 26-month periodicity may be evident at ionospheric heights led Stacey and Westcott[15] to examine geomagnetic and ionospheric data and they found peaks at 26 months in power spectra of monthly mean values of geomagnetic field at two equatorial stations. This particular analysis now appears to be suspect, but a more sensitive method of recognizing the 26-month periodicity in long series of geophysical data shows that sunspots, certain meteorological data and probably geomagnetic field all have a coherent cycle of small amplitude and a period of 25.7 ± 0.2 months. It now seems most likely that the 25.7-month cycle in solar activity is ultimately responsible for all of the atmospheric effects with this periodic tendency, but the mechanism is not understood.

King-Hele[17] has reported the major changes in atmospheric density above

300 km, where satellite-drag data are available from 1957. Since the 1957–58 sunspot maximum, the average density has decreased by a factor of 5 at 400 km and 30 at 600 km. There is also a diurnal variation of a factor of 10, which is however less surprising than the long-term change. During enhanced solar activity the magnetosphere evidently increases in density simultaneously with its contraction in size. The magnitude of the changes makes it surprising that evidence of the 11-year solar cycle is so lacking in meteorological data.

At the present time there is insufficient evidence for a satisfactory quantitative discussion of any of these problems. They represent a new frontier in meteorology and require new techniques for their investigation. Although satellite research is essential, conventional meteorology is by no means helpless and even existing records may contain unsuspected clues on magnetospheric control of the weather, such as the change in distribution of ozone (Kulkarni[18]) and even of the atmospheric circulation at 300 mb (Woodbridge *et al.*[19] and Macdonald and Roberts[20]) following magnetic storms.

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NOTES AND NEWS

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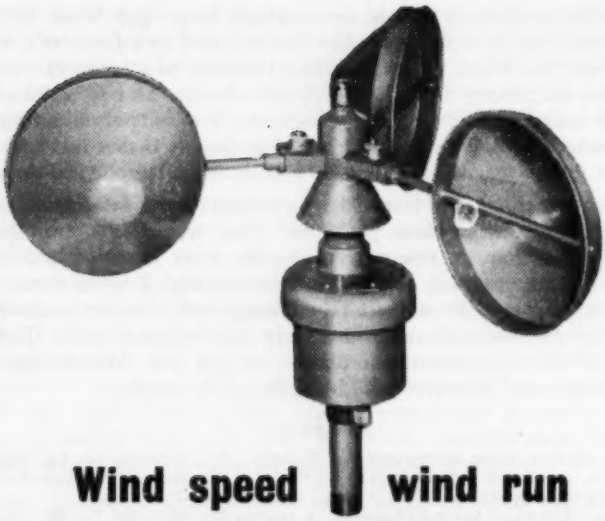

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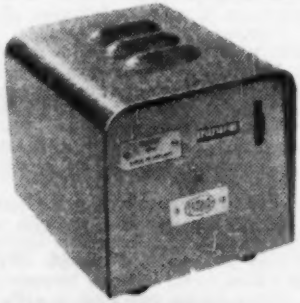

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THE METEOROLOGICAL MAGAZINE

VOL. 93 NO. 1098 JANUARY 1964

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NOTICES

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Printed in England by S. Cockburn & Son Ltd., Ossett, Yorks.
and published by

HER MAJESTY'S STATIONERY OFFICE

Three shillings monthly Annual subscription 39s. including postage

S.O. Code No. 40-43-64-1